The Diego Cao channel and its morphological depressions (Guadalquivir Bank margin uplift, Gulf of Cadiz). Oceanographic and sedimentary implications

El Canal de Diego Cao y sus depresiones morfológicas (margen del Banco del Guadalquivir, Golfo de Cádiz). Implicaciones oceanográficas y sedimentológicas

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Abstract: The Diego Cao channel is located on the central-north middle slope of the Gulf of Cadiz. It separates the Bartolomeu Dias and Faro sheeted drift plateaus to the north of the Guadalquivir Bank margin uplift. A striking linear series of circular depressions occur parallel to the channel on the Bartolomeu Dias sheeted drift (western channel flank), while a remarkable amphitheater-shaped escarpment affects the channel eastern flank. Their morphological and high- and medium-resolution stratigraphic analysis allows inferring their origin as the result of a complex interplay between oceanographic (bottom currents), mass-wasting and tectonic processes. All features seem to have a common origin, related to an especially active tectonic phase during the Mid-Pleistocene, probably related to adjustments of the deep structural features. Since then, the action of the bottom currents and the local influence of structural processes have shaped the present-day topography. The Diego Cao channel is re-interpreted as a contourite moat associated to a complex mounded, separated drift that includes the circular depressions. They result from contourite deposition over the erosional surface originated by widespread mass-wasting events during the Mid-Pleistocene.

Key words: *Gulf of Cadiz, Contourite Depositional Systems, Morphological depressions, Seismic stratigraphy, Mediterranean Outflow Water*

1. INTRODUCTION

Depressions on the seafloor have been widely studied but their origin is still controversial and has been associated to a range of processes, such as collapse, fluid-escape, mass-wasting or bottom current erosion and/or reworking. Different types of depressions have been defined as *sub-circular depression structures*, *subcircular-to-oval scour hollows*, *elongate-to-irregular erosional scours*, and *arcuate to circular slide scars*, many of them associated to contourite depositional systems (Hernández-Molina *et al.*, 2008; Rebesco *et al.,* 2014; Stow *et al.*, 2009).

The Gulf of Cadiz continental slope hosts one of the better-studied Contourite Depositional System (CDS) related to the outflow of the Mediterranean waters into the Atlantic Ocean, and the important interaction between the associated oceanographic processes with tectonism, fluid escape and mass-wasting. This work deals with the depressions that affect the rims of one of the main erosional features composing the Gulf of Cadiz CDS: the Diego Cao channel.

2. REGIONAL SETTING

The Diego Cao channel is located in the central north middle slope of the Gulf of Cadiz (Fig. 1; Llave *et al.,* 2001; García *et al.*, 2009). It separates two sheeted drift plateaus (Bartolomeu Dias to the west and Faro to the east) and it is one of the contourite channels composing the "Channels and Ridges sector" of the Contourite Depositional System (Hernández-Molina *et al.,* 2006). This sector especially reflects the interaction between the MOW flow and the deep sea topography. After exiting the Strait of Gibraltar towards the Gulf of Cadiz, the MOW is split into an Upper Core flowing along the base of the upper slope and a Lower Core that is further split into branches (Southern, Principal and Intermediate branches) by the effect of the NE-SW-oriented diapiric ridges of the middle slope (Fig. 1; Nelson *et al.,* 1999). The Intermediate Branch flows northward along the Diego Cao channel. Above the MOW, the Atlantic Inflow Water is composed of the Surface Atlantic Water and the Eastern North Atlantic Central Water and flows eastward at water depths of up to about 500 m.

The most important structural features are the NE-SW-oriented buried and outcropping diapiric ridges (Maestro *et al.,* 2003), the Guadalquivir Bank basement high and the San Marcos-Quarteira Fault Zone, that roughly coincides with the Diego Cao channel trend. Stratigraphic works reveal a Pliocene record consisting of a pre-contourite and an early contourite phases limited by the lower Pliocene discontinuity (LPD; ~4.2 Ma) and a Quaternary record reflecting a late contourite phase (Llave *et al.*, 2011, 2007). Two Quaternary units are limited by the Mid-Pleistocene Discontinuity (MPD; 0.9-0.7 Ma) and include depositional sequences limited by hiatuses and shifts in depositional processes that resulted from regional tectonic events and margin instability (Hernández-Molina *et al.,* 2014).

3. MORPHOLOGICAL AND SEISMIC STRATIGRAPHIC CHARACTERIZATION

The Diego Cao contourite channel separates the Faro and Bartolomeu Dias sheeted drift (SD) plateaus (Fig. 1). It is about 55 km long with a SE-NW to ESE-WNW trend. Its SE part displays a symmetric and step-like profile and is about 16 km wide and up to 300 m deep. The central part narrows to about 4 km and has an asymmetric profile, with maximum depths of around 270 m and a steeper NE flank corresponding to the Faro SD plateau (17°). Some small reliefs, up to 15 m high, occur on the central channel axis. The NE flank and channel axis are characterized by truncated reflections whereas the SW flank displays layered reflections that pinch out towards the axis (Fig. 2). Small transparent-chaotic bodies locally overlay truncated and strongly deformed layered reflections along the channel axis at the foot of small escarpments on the SW flank.

A remarkable amphitheater-shaped escarpment occurs on the NE flank of the Diego Cao channel, delimiting a terrace that opens to the channel with a diameter of 5.5 km and an area of about 80 km^2 (Figs. 1B, 2). The escarpment walls are up to 100 m deep and ~20° steep and display parallel truncated reflections. Some smaller escarpments occur along the proximal SW channel rim on the Bartolomeu Dias SD plateau. They are 2.5-3 km in diameter and 20-40 m deep and dip towards the channel (SE to NE).

A series of elliptical-circular depressions occur at the eastern side of the Bartolomeu Dias SD plateau (Figs. 1B, 2). They line up for about 12 km in a direction parallel to the channel and close to its rim. Their SW limits show a morphological continuity with the small escarpments described before. Depressions are irregular, 1-2.2 km in diameter and 15-90 m deep. Layered wavy reflections are truncated at the walls and along internal discontinuities (Fig. 2).

The seismic stratigraphic analysis reveals a pre-Quaternary record including a Paleozoic basement that outcrops at the Guadalquivir Bank. Several diapiric structures occur especially on the Faro SD region and are associated with faults that deform the adjacent sedimentary bodies (Fig. 2). The Pliocene record is characterized by stratified reflections on the

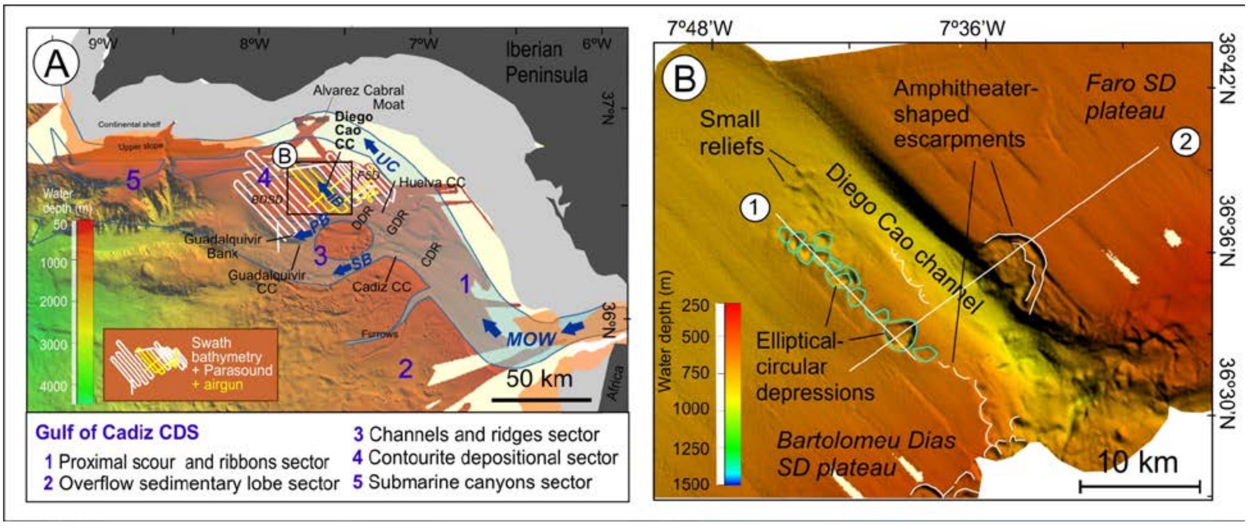

Fig. 1. A) Location of the study area on the middle slope of the Gulf of Cadiz with the distribution of depositional processes of the Contourite Depositional System. The bathymetric and seismic profile tracks are shown. UC: Upper Core; SB: Southern Branch; PB: Principal Branch; IB: Intermediate Branch; DDR, GDR and CDR: Doñana, Guadalquivir and Cadiz Diapiric Ridges B) Detailed bathymetric shaded relief model of the Diego Cao channel area. The main morphological features are shown, as well as the location of the profiles displayed in Figure 2.

sheeted drift plateaus that are deformed by the basement highs and diapiric structures and are truncated by an erosional step-like surface along the Diego Cao eastern flank.

The Quaternary record includes two units, QI and QII (Fig. 2). The lower QI unit is limited at its base by the BQD boundary and at its top by the Mid Pleistocene Discontinuity (MPD). It is composed of medium-high amplitude parallel or subparallel seismic reflections along the sheeted drift that are concordant with the boundaries except on the area with the elliptical-circular depressions, where they are truncated by a distinct erosive surface (Fig. 2). QI reflections are truncated by the Diego Cao channel western wall and by the amphitheater-shaped escarpments and are affected by numerous vertical faults and deformed by the basement high and diapiric structures.

The unit QII is limited by the lower MPD boundary and the present-day seafloor surface (Fig. 2). It is similar to the QI unit, except for the predominance of parallel internal configuration that extends to the limits of the unit and a significantly smaller deformation. On the depressions on the Bartolomeu Dias SD the unit QII displays a complex reflection pattern overlaying the erosive surface at the base of the unit. Seismic profiles orthogonal to the Diego Cao channel show the vertical stacking of units that prograde towards the channel axis (Fig. 2). In contrast, a seismic profile parallel to the channel, along the axis of the circular depressions, presents cut-and-fill packages with downlap and truncation terminations and limited by discontinuities related with deep faults (Fig. 2). Layered reflections are also truncated at the Diego Cao channel wall and at the amphitheater-shaped escarpments.

4. ORIGIN OF THE DEPRESSIONS BY THE INTERPLAY BETWEEN SEDIMENTARY PROCESSES

The morphology and acoustic characteristics of the amphitheater-shaped escarpments suggest a primary origin as mass-wasting features. A structural control is suggested by the numerous vertical faults on the regions where slide scars occur. Faults seem associated to the Guadalquivir Bank margin uplift or to adjustments of the diapiric ridges and/or the AUGC (Maestro *et al.,* 2003) that are also evidenced by the strong deformation of the layered reflections.

The escarpments are continuous with the eastern rim of the circular-elliptical depressions, along which the erosional surface identified in the seismic records outcrops (Fig. 2). This surface can be correlated with the MPD, allowing its interpretation as a mass-wasting feature of this age, which probably allowed

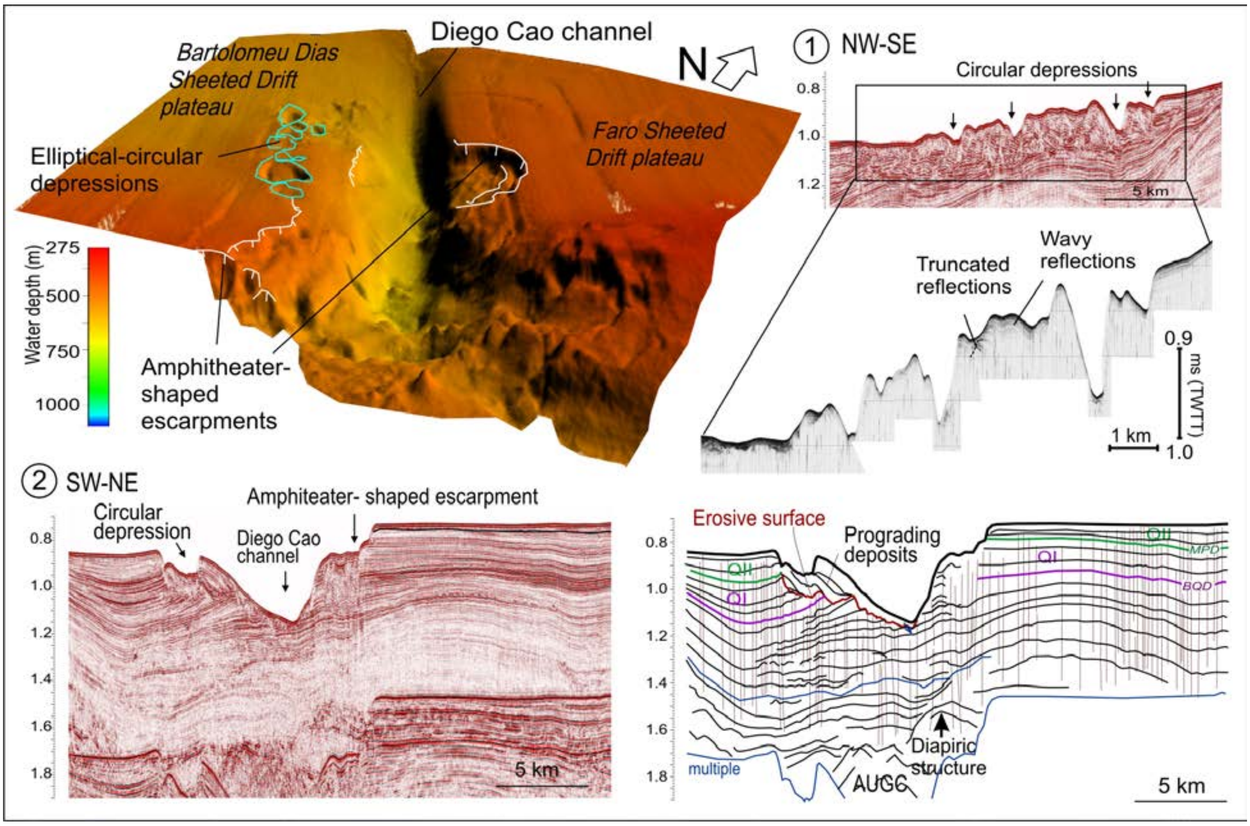

Fig. 2. 3D view of the Diego Cao channel showing the elliptical-circular depressions and amphiteater-shaped escarpments. Seismic profiles (Parasound and Airgun) reveal the main morphological and seismic characteristics.

the onset of the Intermediate Branch of the MOW along the structurally-controlled Diego Cao channel. The intense erosion along the Diego Cao channel also agrees with a vigorous MOW circulation related to the global climatic changes that characterized the mid-Pleistocene (Llave *et al.,* 2001, 2007).

The sedimentary body overlying the erosional surface is interpreted as a complex contourite drift deposited after the Mid-Pleistocene. The depressions would result from the interaction between the bottom current and the semi-circular geometry of the basal surface. Current swirls or vertical eddies would originate the circular-shaped features, in a complex erosional-depositional pattern, probably also favored by the presence of deep faults. Slide scars on the channel wall and transparent deposits on the channel axis suggest that mass-wasting processes are presently active, at least locally. The sedimentary body containing the depressions can be therefore classified as a particularly complex mounded separated drift.

These results suggest that that the Diego Cao channel is a contourite moat, associated to a separated drift with a complex morphological character that differ from the classical mounded geometry described in most models of contourite depositional features. This study highlights the importance of tectonic deformation related to the Mid-Pleistocene Discontinuity (Llave *et al.,* 2007, 2011; Hernández-Molina *et al.,* 2014b) as a crucial episode responsible for the widespread mass-movements that affected the Guadalquivir Bank margin uplift area and determined the widening and deepening of the Diego Cao channel and its evolution as a contourite moat.

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